SUBSTRUCTURE IN CLUSTERS CONTAINING WIDE-ANGLE TAILED RADIO GALAXIES. I. NEW REDSHIFTS

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ABSTRACT

We present new redshifts and positions for 635 galaxies in nine rich clusters containing Wide-Angle Tailed (WAT) radio galaxies. Combined with existing data, we now have a sample of 18 WAT-containing clusters with more than 10 redshifts. This sample contains a substantial portion of the WAT clusters in the VLA 20 cm survey of Abell clusters, including 75% of WAT clusters in the complete survey (z ≤ 0.09), and 20% of WAT clusters with z > 0.09. It is a representative sample which should not contain biases other than selection by radio morphology. We graphically present the new data using histograms and sky maps. A semi-automated procedure is used to

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search for emission lines in the spectra in order to add and verify galaxy redshifts. We find that the average apparent fraction of emission line galaxies is about 9% in both the clusters and the field. We investigate the magnitude completeness of our redshift surveys with CCD data for a test case, Abell 690. This case indicates that our galaxy target lists are deeper than the detection limit of a typical MX exposure, and they are 82% complete down to R=19.0. The importance of the uniformity of the placement of fibers on targets is posited, and we evaluate this in our datasets. We find some cases of non-uniformities which may influence dynamical analyses. A second paper will use this database to look for correlations between the WAT radio morphology and the cluster’s dynamical state.

Subject headings: galaxies: clusters: general galaxies: distances and redshifts galaxies: jets

1. Introduction

Wide-angle tailed radio galaxies (WATs) are a powerful type of FR-I (“edge-darkened”, Fanaroff & Riley 1974) radio galaxy associated with first-ranked ellipticals in clusters. Generally, the tails of a WAT bend in a common direction, giving the source an overall V, or C shape (see O’Donoghue et al. 1990 for a radio survey). The mechanism which bends the WATs is poorly understood. Ram pressure caused by motion through the intracluster medium (ICM) was suspected from the time of discovery (Owen and Rudnick 1976). The sticking point in this hypothesis is that \( \approx 1000 \) km s\(^{-1}\) relative velocities may be required for bending (Eilek et al. 1984), and the host galaxies, typically gE, D and cD, should have much smaller peculiar velocities with respect to their cluster (Malumuth 1992, Burns 1986).

A subcluster merger hypothesis has emerged linking the bent morphology of WATs to the dynamical state of the host cluster (Pinkney et al. 1993, hereafter Pi93, Gomez et al 1997, Roettiger et al. 1996, Loken et al. 1995). In it, the WAT acts as a stationary weathervane, its tails indicating the local flow of ICM in the stormy environment of a cluster-subcluster merger (Burns 1998). If this hypothesis is true, then WAT’s should be beacons of cluster mergers.

This hypothesis is difficult to confirm for a single cluster: only radial peculiar velocities can be ruled out for the WAT galaxy, and the optical signatures of merger can be subtle during post-merger epochs when the ICM motion is still sufficient to shape the WAT (Loken et al. 1995; Pinkney et al. 1996). A large database can provide statistical leverage to test the subcluster-merger hypothesis. In particular, a distribution of WAT radial peculiar velocities can constrain the true WAT velocities, thereby testing the moving-WAT hypothesis. Moreover, the occurrence rate of significant substructure can be compared to a control sample of radio-quiet clusters. In this paper, we present new velocities and positions of over 600 galaxies in 9 WAT clusters. This will
be combined with published data for 9 additional WAT clusters. These data will be used to probe
the connection between WAT bending and cluster evolution in paper II. In this paper, section 2
will contain the sample selection criteria. Section 3 describes the observations and reductions.
In section 4, we compare our velocities to published ones and discuss the emission line content.
Finally, in section 5 we examine the completeness and spatial uniformity of our redshift surveys.

2. WAT Cluster Sample Selection

Our primary selection criterion for clusters was radio morphology. Clusters with high
resolution radio data were preferred; if there is a morphological trait among WATs that correlates
with their dynamical state, we want it to be apparent in the existing maps. We also required
galaxies with $m_V < 18.0$ (Pinkney et al. 1994, hereafter Pi94), and $\delta < 72^\circ$ for observation with
the Steward Observatory 2.3-m telescope + MX spectrometer.

Our resources for sample selection include the VLA survey of 11 WATs by O'Donoghue et al.
(1990, hereafter OOE), and the 20 cm VLA Survey of Abell Clusters (Owen & Ledlow 1997
and references therein). This survey contains 38 radio sources informally classified as “WAT” or
“WAT?”, 8 of which comprise 2.3% of the complete cluster sample ($0.0 \leq z \leq 0.09$). The survey
uses the VLA C-array (1.4 GHz), with adequate resolution (3-15″) to reveal the WAT morphology
out to $z \sim 0.2$. The VLA maps in OOE generally have higher resolution and sensitivity. Therefore,
we attempted to draw as many clusters from this survey as possible. However, several of the OOE
clusters are beyond the redshift and declination limits of the MX spectrometer. We emphasize that
we did not select WATs by the apparent angle formed by their tails as it might bias the peculiar
velocity measurements. Fortunately, the OOE survey included a wide variety of morphologies, so
that WATs with strongly bent and weakly bent tails were present.

We obtained new optical spectra for 7 Abell clusters from OOE: A98, A160, A690, A1446,
A1684, A2214, and A2462, and for 1 Abell cluster not in OOE, A2220. Together with the
published databases for A115 (Beers, Huchra, & Geller 1983), A400 (Beers et al. 1992), A623 and
A2304 (Gomez 1998), A1346 (Slinglend et al. 1998), A1940 (Huchra et al. 1992), A1569 (Gomez
et al 1997), and A2634 (Pi93, Scodeggio et al. 1995), we have redshift databases for 16 Abell
clusters with WATs.

In addition, we observed a poor cluster containing the WAT 1313+073 (Patnaik et al 1986).
We will also include the published database for the poor cluster containing the WAT 1919+479
(Pi94). Both are good examples of the WAT morphology with excellent radio maps available.
We argue that inclusion of these poor clusters is appropriate in this study because the X-ray
and radio properties of poor and rich clusters overlap (Price et al. 1991, Burns et al. 1996), and
redshift-corrected membership counts of poor clusters overlap those of richness class 0 and 1 Abell
clusters (Andersen & Owen 1994).

The radio properties of our combined sample of 18 WATs are shown in Table 1. This sample
contains 6/8 (75%) of WAT clusters in the complete 20 cm VLA survey \((z \leq 0.09)\), and 7/30 (23%) of the WAT clusters in the high redshift portion of the VLA survey. The ROSAT X-ray data for five of these clusters were discussed in Gómez et al. (1997). The quantities “Extent”, \(r/A_C\), and \(\log(P_{1400})\) in Table 1 might all conceivably be correlated with global cluster properties. We will return to these in paper II.

### 3. Multifiber Spectroscopy

The spectral observations of cluster galaxies were made with the MX multifiber spectrometer (Hill & Lesser 1986) on the Steward Observatory 2.3-meter telescope. The MX uses mechanical probes to position 2″ diameter fibers in the focal plane with 0.″5 precision. The useful field diameter is 45′. Up to 32 fibers are assigned to galaxies, while 29 are placed on the sky.

Our initial detector was a TI 800x800 CCD which became unreliable after our Dec. 31, 1991 run (Table 2). For the remaining runs, we used Loral 1200×800 CCDs. The Loral chips had a superior full well capacity, readout noise, and Q.E. (which exceeded 90% at 4000Å). Our first Loral chip had a problem with excessive ‘cosmic rays’ caused by a radioactive coating on the chip. On the next run, the second Loral chip lacked the radioactive coating. However, it had a problem with large gradients in bias which varied with time. This problem was handled in reduction by replacing standard bias subtraction with subtraction of a surface fit to inter-aperture counts. The old 300 lines/mm diffraction grating was switched with a 400 lines/mm grating (4890Å blaze) for the Dec 1992 run. This changed the dispersion from 3.6 to 2.6 Å pix\(^{-1}\) and the spectral resolution improved from 8.3 Å to 6.1 Å. After two useful runs with the second chip, a third Loral chip was used which had a stable bias level. Some sample spectra from our surveys are shown in Figure 1. The spectral range was nominally reduced to 3800-6900 Å for cross-correlation.

Our basic CCD reduction, spectral extraction and cross-correlation procedures are much the same as in Pi93 and Pi94. Post-correlation reduction includes a new, objective algorithm for combining the velocities produced by 21 templates. This algorithm uses the \(r\) value of the CCF (cross-correlation function, Tonry & Davis 1979), and the number of templates agreeing on the same velocity (within a 600 km s\(^{-1}\) range) as criteria for including or excluding velocities in an average. We use three categories for a galaxy’s final velocity measurement, category 1 (hereafter C1), those with an average \(r\) value \(\geq 3.5\) and at least 4 templates in agreement; category 2 (hereafter C2), those with \(3.0 \leq r < 3.5\) and at least 4 templates in agreement; and “invalid”, those which do not fall into the above categories. The C2 category includes velocities which are \(\geq 50\%\) likely to be determined from the correct peak in the CCF. Therefore, C2 galaxies can be classed as cluster members or non-members with some accuracy, but should be omitted from analyses of the velocity distribution. The \(r\) value was also used in combining redundant observations of galaxies: spectra with low \(r\) were excluded from the velocity determination if high \(r\) spectra existed. The final velocities and positions are tabulated in Table 3. The fourth and fifth columns contain the C1 and C2 velocities, respectively. Galaxies with invalid measurements, with
no measurements, and stars, are omitted.

To determine the velocity errors (column 6, Table 3), we fitted a curve to the relation between velocity deviation and the $r$ value of the CCF (similar to Pi94, Hill & Oegerle 1993). We used 251 repeat spectra of galaxies from 4 clusters taken with the Loral CCD systems for this calibration. The resulting fit is $\epsilon(r) = 486.7(1.0 + r)^{-1}$. When three or more good spectra were obtained, the standard deviation was used as the velocity error. If the calculated errors were less than 20 km s$^{-1}$, the final velocity error was set to 20 km s$^{-1}$. The last two rules also applied to emission line velocities (see §4.2). An emission line redshift would only be adopted if the cross-correlation results had a larger scatter or $r \leq 4.0$. If only one spectrum existed, the standard deviation of velocities derived from each emission line was used. All C2 velocities were assigned an error of 200 km s$^{-1}$, to discourage their use for purposes that require greater velocity precision.

4. The WAT Velocity Database

A collage of histograms is shown for our nine new datasets in Figures 2 and 3. It is clear that the WATs are associated with real systems in redshift space. Also, visual inspection of these figures reveals obvious velocity substructure in clusters such as A98, and A160. In Table 4 we summarize the cluster velocity distributions. Here we use the traditional mean and standard deviation and apply them to the velocities within $\pm 4000$ km s$^{-1}$ of the WAT. These estimators of velocity centroid and dispersion are notoriously poor in the presence of outliers or substructure (Beers et al. 1990). In Paper II, we will account for substructure in the datasets and apply more robust estimators to the velocity distribution.

4.1. Comparison with literature

As a check on our velocity measurements, we have compared our results to those published for A2462 (also called A3897, Katgert et al. 1998) and A98 (Beers, Geller, & Huchra, 1982; Faber & Dressler 1977; Zabludoff et al. 1990) in Table 5. Redshifts for A98 were first obtained by Faber & Dressler 1977 (FD) and were added to by Beers, Geller, & Huchra, 1982 (BGH). The average difference between our velocities and those of BGH and FD combined is -67 km s$^{-1}$, with $\sigma=113$ km s$^{-1}$ (N=7). This standard deviation is consistent with random errors in velocity of 80 km s$^{-1}$. Zabludoff et al. (1990) later took the data added by BGH and re-reduced it with a new template. The difference between our velocities and the velocities in Zabludoff et al. are 40 km s$^{-1}$, with $\sigma=157$ (N=5). Two velocities were measured by Faber & Dressler 1977 and ourselves, but not BGH, they differed by -193 and -132 km s$^{-1}$.

We wish to add to our dataset the 21 BGH/FD galaxies which we did not observe. The measured zero-point shift (-67 km s$^{-1}$) is only marginally inconsistent with no shift (1.6$\sigma$), so we will not attempt to correct for it. We have precisely re-measured the positions of the BGH
galaxies on our quick-V frame based on their finding chart. We include them in Table 3, and give them ID’s that begin with “0”.

Table 5 compares the 12 velocities in Abell 2462 which were measured by both ENACS (ESO Nearby Abell Cluster Survey) and us. The mean difference (after removing the 325 km s$^{-1}$ CMB correction used by ENACS) was -98.8 km s$^{-1}$ with a standard deviation of 111.2 km s$^{-1}$. One velocity, ENACS # 12, was adopted since we had no measurement. The ENACS galaxies are labeled in the notes column of Table 3. Our velocities are in reasonable agreement with published values.

4.2. Emission Line Galaxy Survey

We searched our data for emission line galaxies (ELGs). The primary goals were to strengthen the accuracy of the velocity measurements and to increase cluster membership. The codes in column 7 of Table 3 indicate the presence of emission lines in the spectra.

Emission line redshifts were measured in a two-stage process. The first stage identified potential redshift systems using IRAF-based scripts and a Fortran program. Each spectrum was continuum-subtracted and its positive features over $\approx 2\times$RMS were identified. Each feature was fitted with a Gaussian. The features were then searched for redshift systems containing any 2 or more of 15 lines produced by [OI], [OII], [NeIII], [OIII], [NI], [NII], [SII] or the Balmer series. To reduce spurious results, the program rejected features that were: 1) too close to 4 major night sky lines, 2) too thin (FWHM $\leq 3.8$ Å), 3) too wide (FWHM $\geq 25$ Å), or 4) too low in flux (< 20 DN). The program ranked the systems based upon how well their features agree in redshift, and the number of features they contain.

In the second stage, the output from the automated search was used as a guide to judge the final validity of each system. We judged redshift systems based on the line id’s, fluxes, FWHM, redshift agreement with each other and agreement with cross-correlation results. We also visually inspected the candidates to look for lines missed by the automated search, and to choose between the redshift systems. A spectrum had to have at least 2 lines of [OII], [OIII] $\lambda 5007$, H$\beta$, or H$\alpha$ to be acceptable, while lines of [OI], [OIII] $\lambda 4363$, [NeIII], and [NI] were insufficient. Moreover, we expected line ratios to be typical of astrophysical environments, e.g., the [OIII] $\lambda 4959$ line flux should not be much larger than that of $\lambda 5007$, and H$\beta$ should not be larger than H$\alpha$. Convincing lines typically had FWHM $\geq 6$ Å and rarely exceeded 15 Å. The sensitivity limit in equivalent width was roughly -5 to -10Å. Real line systems typically had internal scatter $\lesssim 100$ km s$^{-1}$. An example of a convincing ELG spectrum is shown in Fig 1c.

We show the results of our ELG survey in Table 6. Here we see a range of 0 - 20% in the percentage of cluster members with emission, with an average of 8.6%. As a comparison, Biviano et al. (1997) find $\approx 16\%$ in the ENACS database, although they have perhaps less stringent criteria (1 emission line is sufficient). Each of our percentages should be considered a lower limit to the
true ELG percentage because many factors reduce our detection of emission lines. The positioning
of the Hα line within the spectral range was the main factor (see Table 6). Abell 160 has the
highest ELG% and this is probably related to the frequent inclusion of Hα within the spectral
range. Another factor is the confusion of galaxy emission with night sky lines. Some members
of A98 and A1446 will have their [OIII] redshifted near λ5577, and the automated program will
reject any line within a window centered on that line. Despite this, the ELG% for A1446 appears
high. However, the ELG fraction for non-members in the A1446 field is also high, suggesting that
excellent data quality is the cause rather than cluster properties. In general, our data are not
sufficiently homogeneous to make direct comparisons between ELG fractions in our clusters. The
bottom row of Table 6 indicates that the apparent fraction of ELGs is roughly the same among
our member and non-member (“field”) samples. This coincidence results from our particular
detection limits for ELG’s and non-ELG’s. Biviano et al. (1997) find an apparent fraction of ELGs
among the field about 2× greater than inside clusters (a real field-cluster difference is expected
because of morphological segregation). Given that their search criteria are less stringent than
ours, their sensitivity to ELG’s is higher in both environments. But the fraction of ELGs will be
disproportionately higher in the field because it contains mostly spirals. So it is not surprising
that our results differ.

5. Spatial sampling and magnitude completeness

For many cluster analyses, it is important that the candidate galaxies in the cluster fields
are evenly sampled. Radial variations in sampling will result in misrepresentation of the cluster
velocity dispersion and mass if there is a non-constant dispersion profile. Azimuthal variations can
result in overlooking subclusters that are kinematically distinct. Splotchy sampling in general can
cause false positives in substructure tests that are sensitive to bimodality or asymmetry (Pinkney
et al. 1996). Thus, one should be aware of the spatial uniformity of one’s cluster redshift survey.
Moreover, if one wishes to compare the occurrence rate of substructure in one survey to another,
it is desirable to know the depth and area of coverage in both surveys. We will address these
issues as follows: first, we describe how our lists of galaxy candidates were created, second, we
will estimate the completeness of these lists (hereafter, MX files), and third, we will evaluate how
evenly we placed fibers on the candidate galaxies.

5.1. Candidate galaxy selection

The cluster search fields were roughly square with sides of 3 h_{75}^{-1} Mpc (Table 7 gives
dimensions) and centered on the WAT. A digitized image was obtained from the “Quick-V”
survey (DSS). Galaxies were selected by inspecting prints of the Palomar Sky Survey (PSS)
with a binocular magnifier. Objects were circled on a hardcopy of the DSS image and given
priorities to be used in fiber placement. We included galaxies below the magnitude limit for
reliable cross-correlation (estimated from early data). We also included faint, compact objects which showed slight “fuzz” or asymmetry. The poor candidates were given low priorities so that obvious galaxies would be observed first. Coordinates were then measured to $\lesssim 0.5''$ precision on the DSS images using the Guide-star Astrometric Support Package (GASP). These coordinates were assembled into an $MX$ file for each cluster. Finally, the MXPACKAGE tasks in IRAF$^2$ are used to select targets for individual exposures. We iterated on the priorities after observing runs to eliminate the stars.

5.2. Completeness of candidate galaxies and depth of spectra

To address the completeness of our $MX$ files we used new CCD data obtained for Abell 690 at the M-D-M 1.3-m on Jan 4, 1999. We used a 2048$^2$ STIS CCD with 0.44 $''$/pix. We obtained 1160 sec of total exposure in each of the V and R filters. The dithered exposures were combined to make a 14.4 x 15.0 image (1.15 x 1.20 $h^{-1}_{75}$ Mpc). The gibbous Moon made the images noisy and difficult to flatfield; our limiting magnitude was R=21.2 (2.5$\sigma$). The FWHM of the PSF was about 1$''$.8.

The detection and classification of objects in these frames were done using SExtractor (Bertin & Arnouts 1996) in double-image mode. SExtractor provides a “stellarity index” (hereafter, $SI$) which corresponds roughly to a confidence limit (1=stellar, 0=non-stellar). SExtractor could rule out stellarity with 95% confidence ($SI \leq 0.05$) down to R=19.0. We used an adaptive aperture magnitude which included all but $\approx 10\%$ of the light for galaxies. A photometric calibration using Landolt standard stars allowed us to set the zeropoint. A comparison to 11 field stars in the USNO-A01 (Monet et al. 1996) gave a zero point offset of 0.16 mag, which is less than the USNO plate-to-plate errors. We also estimated our scatter to be $< 0.13$ mag.

The total number of $MX$ file objects in the CCD field was 79. SExtractor classified 50 of these as non-stellar, with $SI \leq 0.2$, 18 as ambiguous objects ($0.2 \leq SI \leq 0.8$), and 11 as stellar ($0.8 \leq SI \leq 1.0$). The numerous ambiguous and stellar objects mostly appear faint and/or compact on the PSS and were given low priorities. Most of the $SI \geq 0.8$ objects are stars, but we measured a C1 galaxy velocity for one object with $SI = 0.98$. Five more examples of C1 galaxies were found with $0.2 \leq SI \leq 0.8$. Had our $MX$ candidates been selected based on these $SI$ results, several real galaxies would have been omitted. This underscores the possibility that compact galaxies are often overlooked in redshift surveys (Drinkwater et al. 1999). SExtractor also erred in the opposite sense, classifying stars as galaxies, particularly where the PSF distorted near the field edge. The 3 brightest of these were omitted from the following.

The completeness of our A690 $MX$ file is plotted in Fig 4. The solid line is the fraction of

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$^2$IRAF is distributed by the National Optical Astronomy Observatories, which is operated by AURA under cooperative agreement with the NSF.
CCD galaxies that are included in the *MX file*. There are 4 omissions in the R=16.75 and 17.25 bins. Two of these galaxies were in fact spotted on the PSS, but failed to be catalogued because of mistakes in bookkeeping. One was excluded from MX because of its proximity to a bright star. One CCD object was overlooked. The fainter, R=17.75 bin is 100% complete. In R=18.75, the completeness of our *MX file* is about 70%, and it quickly drops thereafter. Combining all bins with R≤ 19.0, the A690 *MX file* is 82% complete. Thus, we find that our method of galaxy selection is also subject to errors, but few of these are oversights.

We suspect that our other *MX files* were not equally deep. Table 7 shows the number of candidate galaxies for each cluster, “N\textsubscript{Cand}”, which is a measure of how thoroughly the PSS prints were searched for candidates. However, it must be modulated by the the cluster richness count (R), search field size (Field), field star density, and redshift (Table 6). It appears that A1684 and A2220 have relatively small candidate lists for their richness, field size, etc., and thus are likely to have lower completeness. In contrast, A2462 has a relatively large N\textsubscript{Cand}.

If all *MX files* are far deeper than the limit of the detector, the variations are inconsequential. We have examined the limit of detection by the 2.3-m + MX using the A690 CCD data. We consider a “detection” to be a spectrum with a reliable (C1) redshift. We do not expect a sharp magnitude limit because the detectability should vary with observing conditions, the compactness and spectral type of the galaxy, etc. We find that, for 1 hour exposures, about 50% of objects with 18.0 < R < 18.5 provided C1 redshifts. Below this, the number of C1 results declines rapidly. This suggests a rough limit of R≈ 18.5. However, our probabilities are boosted in the case of A690 because most of its galaxies were observed repeatedly. Thus, R≈ 18.5 is the limit under the best conditions. For a single exposure in average conditions, the magnitude of 50% probability is probably brighter than R≈ 18.0 (Cf. R≈ 17.25, Pi94). Since over half of the *MX file* objects in the A690 CCD field were fainter than R=18, our *MX files* appear deeper than the MX limit. Also, our target priorities cause the brightest galaxies to be observed first. Thus, any variations in the depth at which we surveyed the PSS prints should not seriously affect the depth of our detections.

We have shown that the *MX files* are nearly complete down to the detection limit of the instrument (R≈18.5). But how many objects were actually observed to this depth, and how many yielded reliable redshifts? The dotted line in Fig. 4 indicates the fraction of A690 objects with \(SI \leq 0.2\) for which a spectrum was obtained. We have a spectrum for 68% (34/50) of all \(SI \leq 0.2\) objects brighter than R=18.5, and a C1 redshift for 50% . Since this sample defined by SExtractor omits at least 6 galaxies and includes stars, let us take the sample of 79 *MX file* objects contained within the CCD field and remove objects with \(SI \geq 0.2\) and R>18.5. Then we have a spectrum for 95% and a C1 redshift for 61%. Lacking a definitive list of galaxies in the field, we estimate that about 60% of the galaxies in A690 have reliable redshifts down to the MX limit (R=18.5).

The other WAT clusters may differ in completeness. Table 7 shows the *sampling percentage* (“%”), or the percentage of *MX file* objects that were observed. For A690, the sampling percentage is 76.4%, which ranks 3rd from highest. The 1st and 2nd ranked percentages are for A1684 and
A2220, but since these have a relatively small number of candidates ($N_{\text{Cand.}}$), A690 is probably deeper. A690 had 19 exposures which should boost its completeness considerably. The clusters with the lowest sampling percentages, A1446 (42.4%) and A2214 (52.1%), are likely to have lower completeness levels because of the low number of exposures. The cluster with the lowest percentage, A2462 (34.5%), may not be especially incomplete because it has a very large catalog ($N_{\text{Cand.}}=444$) for its richness (0).

In summary, the completeness of our A690 MX file is 82% down to $R=19.0$ and other clusters should scale roughly by $N_{\text{Cand.}}$. The sampling of our well-observed clusters (e.g., A690) is very high (about 95% to $R=18.5$) resulting in reliable redshifts for about 60%. Unfortunately, some of our clusters require more observations for this level of completeness. For example, we are in danger of missing substructures in A1446 and A2214 where the sampling drops below 40% in subregions.

5.3. Spatial fairness of sampling

We were concerned with obtaining uniform spatial coverage of our clusters. The priorities we assigned to the objects in our MX files were used to control this. MXPACKAGE would reduce the priorities to avoid repetitions in consecutive exposures, and we manually reduced the priorities from night to night to better sample all the galaxies. We further influenced the spatial coverage by the choice of a center star for guiding. This made different regions of the field accessible to the probes. Finally, the density of fiber probes as a function of radius was also adjustable by the user.

We have evaluated how evenly we sampled the candidate galaxies by dividing the cluster search fields into 6 subregions. These subregions are shown in Figure 5 for A690 and A2634. The subregion sampling percentages for each cluster are summarized in Table 7. Abell 1684, and 2214 appear to be undersampled in their centers compared to their outer regions. The difference between these two counts is only significant at the 1.3 and 2.3 $\sigma$ level, respectively. These are fairly distant clusters with less than 5 exposures, so their cores were not thoroughly probed. Abell 2462 and 2634 are over-sampled in the center compared to the outer regions at the 4.9 and 3.1 $\sigma$ levels, respectively. A2634 also shows a significantly deficient SW quadrant. Abell 160 is marginally over-sampled in the center (2.8 $\sigma$). The other clusters (including A690 in Fig. 5) are reasonably evenly sampled. Thus, we find 3$\sigma$ non-uniformities in 2 cases, A2462 and A2634, and 4 other less significant cases: A160, A1684, A2214, and A2220. Even the less severe non-uniformities could influence substructure analysis and velocity dispersion measurements. We will keep this in mind for our analysis in paper II.

6. Summary

We have presented new redshifts and positions for galaxies in 9 WAT clusters. Nineteen of our galaxies had published redshifts which are in reasonable agreement with our redshifts (i.e.,
σ < 150). A search for emission line galaxies helped contribute cluster redshifts and improve the accuracy of our catalog. Our candidate galaxies for observation were chosen by visual inspection of the PSS. CCD data for Abell 690 indicate that its candidate list (MX file) is 82% complete down to R~19.0. Also, 95% of A690 targets are observed, while about 60% of them have reliable redshifts down to the MX detection limit (R~18.5). The fraction of candidates that are observed varies from cluster to cluster, and, for 2 clusters, varies strongly between subregions in the cluster. Nevertheless, the dataset is well-suited for measuring WAT peculiar velocities, and can also be used for substructure analyses with attention to the cases with uneven sampling. Paper II will use these data to look for links between the WAT radio morphology and the cluster’s dynamical state.

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Fig. 1.— Spectra from the MX multifiber spectrometer. The night sky spectrum has been subtracted, but the residuals of prominent lines (marked “ns”) may be visible. a) The WAT in Abell 1684. Note the interference of night sky with Mg b. b) The WAT in Abell 1446. c) A convincing emission line spectrum from A98. d) A galaxy in A98 showing prominent Balmer absorption left of the 4000Å break and slight OII emission indicative of post- or ongoing- star formation.

Fig. 2.— Histograms showing all C1 velocities (see text) measured in the fields of Abell 98, 160, 690, 1446, and 1684. The number of C1 velocities is shown.

Fig. 3.— Histograms showing all C1 velocities measured in the fields of Cl1313+073, Abell 2214, 2220, and 2462. The number of C1 velocities is shown.

Fig. 4.— Plot of completeness vs. SExtractor R magnitude within a 14′4X15′ field of Abell 690. Use the left axis for the two completeness curves and the right axis for the triangles and squares. The solid curve is the fraction of SExtractor galaxies ($SI \leq 0.2$) which are in the MX file (see text). The dotted curve is the fraction of the SExtractor galaxies which were actually observed by MX. The boxes are the number of SExtractor galaxies in each 0.5-mag bin, while the triangles are the number of those SExtractor galaxies which are also in the MX file.

Fig. 5.— Two plots showing the uniformity of spatial sampling for Abell 690 and Abell 2634. The filled circles are candidate galaxies with a spectrum (i.e., “sampled”) and the open circles are candidates without a spectrum. The percentage of candidates observed is labelled inside six sub-regions: four equal-sized quadrants, a region inside of the circle ($D = 1/2$ field height), and a region outside of the circle. These sampling percentages are given for all of the clusters in Table 7. Note that Abell 2634 is undersampled in the lower right quadrant (Q4) and oversampled in the center.
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